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OPTIMAL DEPOT LEVEL MAINTENANCE PLANNING

by

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OPTIMAL DEPOT LEVEL MAINTENANCE PLANNING

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The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

In 1991, the Marine Corps began replacing its aging fleet of M60A1 Main Battle Tanks (MBTs) with M1A1 MBTs. Fielding of the new tanks will be complete in 1997 with 403 M1A1s located throughout the continental United States and onboard ships of the Maritime Prepositioning Squadrons. Given the continuing likelihood of slim defense budgets, providing the costly but vital depot maintenance support for the M1A1 tank fleet is of concern to the Marine Corps. Currently, there is no management tool available to analyze the effects of various maintenance policies. The goal of this thesis is to develop a mathematical model to aid the Marine Corps in establishing an effective and efficient maintenance policy for the M1A1 fleet.

Specifically, an optimization model is developed for analysing effects of maintenance policies on the M1A1 tank fleet. The objective of the model is to maximize the fleet readiness while observing various operational requirements and proposed maintenance policies. The model is implemented in the General Algebraic Modeling System (GAMS) and is used to provide the following recommendations based on a data set projected for 1996 and beyond.

1. The planned distribution of the Plain Jane Upgrade (PJ) version of the M1A1 tanks needs to be revised in order to support the policy of sending tanks to depot maintenance at least every 5000 miles. The planned distribution of PJ tanks is infeasible under this policy and the model suggests that at least 4 additional PJ tanks should be reassigned to the Depot Maintenance Float (DMF).

2. The currently proposed plan uses three maintenance depots at Albany, Georgia; Barstow, California; and Anniston, Alabama. The first two are Marine Corps maintenance depots. The last one is an Army depot that provides maintenance at a higher cost than the other two. The model shows that only Marine Corps depots are needed to support the proposed maintenance policies. Furthermore, Albany and Barstow have more than sufficient capacities to meet the needs of the M1A1 fleet. If the capacities at these two depots are reduced by 1/3, the fleet readiness is still at an acceptable level. In fact, the model estimates that the readiness is only reduced by slightly more than 15%.

3. To maintain stability of operational units, it has been proposed that no more than 25% of the tanks assigned to a unit can be sent to depot maintenance in one year. However, the model shows, for example, that increasing this percentage to 35% and 48% improves readiness on average by 19.8% and 38.67%, respectively, thereby demonstrating that there is a trade-off between readiness and unit stability.

I. INTRODUCTION

The Marine Corps is replacing its aging fleet of M60A1 Main Battle Tanks (MBTs) with M1A1 MBTs. By 1997 approximately 403 M1A1s will be located throughout the continental United States and onboard Maritime Prepositioning Squadron (MPS) ships. In addition to its 4 million dollar price tag, the M1A1 is a maintenance intensive weapon system with numerous preventive and corrective procedures required at the organizational, intermediate, and depot levels. The most costly and extensive of the maintenance requirements are those accomplished at the depot level. The projected expense of over $200,000 per tank [Ref. 1] is an issue of great concern for Marine planners already operating on very slim budgets. Recognizing that the defense budgets of the future will not likely be any more generous than those of today, the Marine Corps is necessarily interested in minimizing the M1A1 maintenance costs at all levels. Being so costly, a great potential for savings lies in the planning and management of depot-level maintenance.

To date, the Marine Corps efforts to establish a maintenance management policy have focused primarily on operational considerations. The current plan is to provide depot maintenance support to 25% of the operational fleet each year by systematically rotating the tanks between the tank battalions, depots, and the MPS ships. This rotation scheme is intended to evenly distribute use among all of the tanks and is viewed as a means of achieving the longest possible lifetime for the M1A1 fleet as a whole. However,

there is currently no model or other management tool available to analyze the effects of this policy over time or to investigate the suitability of alternate proposals.

The objective of this thesis is to develop such a model to aid the Marine Corps in establishing an effective and efficient maintenance policy for the M1A1 tank fleet. Specifically, an optimization based model with an embedded multi-commodity network structure is presented. In the next chapter, additional background is given and important aspects of the problem are explained in greater detail. Chapter III outlines the assumptions of the model, explains the network structure, and presents a mathematical formulation of the problem. In Chapter IV, an implementation of the model is shown and then applied to the analysis of issues crucial to the establishment of an optimal maintenance policy. Finally, conclusions and recommendations are given in Chapter V.

II. PLANNING DEPOT LEVEL MAINTENANCE

In this chapter, information pertinent to planning depot-level maintenance for the M1A1 is presented. The first section describes how the tanks are assigned to the operational units, depots and MPS ships. Then the physical process of effecting depot-level maintenance and current operational policies are explained.

A. DISTRIBUTION OF THE FLEET

The M1A1s are used operationally by the Equipment Allowance Pool (EAP) and by active and reserve tank battalions at the locations outlined below. The active units, the 1st and 2nd Tank Battalions, are located at Twentynine Palms, California, and Camp Lejuene, North Carolina, respectively. Tanks assigned to the EAP support the Combined Arms Exercises (CAX) conducted at the Marine Corps Air Ground Combat Center (MCAGCC), Twentynine Palms. There are two reserve battalions as well. The 4th Tank Battalion has subordinate commands at San Diego, California; Yakima, Washington; and Boise, Idaho. Additionally, the 8th Tank Battalion fields tanks at Fort Knox, Kentucky; Syracuse, New York; Columbia, South Carolina; and Tallahassee, Florida.

In addition to these operational units, the Marine Corps has tanks onboard ships of the three Maritime Prepositioning Squadrons. All three squadrons are based at the MPS offload facility in Blount Island, Florida. These ships are normally staged in strategic areas and their embarked combat equipment is intended for use in crisis situations. The ships

require periodic maintenance and, for this reason, return to the United States on a rotating basis.

Finally, the Marine Corps has two depot maintenance facilities, one at Albany, Georgia, and the other at Barstow, California. The Marine Corps also sends tanks to the Army Depot at Anniston, Alabama. The latter is more costly, however. The combined number of tanks at all depots, either undergoing or having completed maintenance, is considered to be in the Depot Maintenance Float (DMF). On average, a tank sent to depot takes approximately one quarter before becoming available for return to a unit. During this time, the tank is transported from a unit to a depot, usually by rail, receives maintenance, and if required, can be transported back to perhaps a different unit.

The fleet includes two types of MBT - the M1A1 Common (CT) and the M1A1 Plain Jane Upgrade (PJ). The distinction between these two variants is the armor. The M1A1 CT has depleted uranium armor which is more effective in resisting anti-armor weapons than the armor employed on the PJ. The different armor has no effect on the operation or maintenance of the tank. Being the more capable warfighter, the CT is assigned to the active battalions and the MPS only. Table 1 summarizes the planned disposition of the M1A1 fleet.

B. THE DEPOT MAINTENANCE PROCESS

The logistics of conducting depot-level maintenance involves some amount of detail. Recall that there are numerous locations involved with this process: operational units,

Unit	Number of CT	Number of PJ
1stTank Battalion	30	28
2d Tank Battalion	44	14
4thTank Battalion		32
8thTank Battalion		32
EAP		22
MPS I	58	
MPS II	58	
MPS III	58	
DMF	21	6

Table 1. Distribution Of Tank Fleet

depots, and the MPS offload facility. The tanks must be moved between these sites to facilitate depot maintenance support as follows.

When a tank reaches a specified milestone, 5000 operating miles for example, or is otherwise deemed to require depot maintenance, it is transported to one of the depots. In order to maintain operational readiness, the unit does not send the tank until it has received a replacement from DMF. This policy requires coordination at the depot level to ensure that replacements of the appropriate type are available when needed. Otherwise, tanks which are due for depot-level maintenance will not be transported, and consequently, may experience more serious maintenance problems or shortened lifetimes due to the delay.

Besides DMF, the MPS offloads provide an alternate source of tanks which can be used to replace those sent to the depots. Roughly every other month an MPS ship comes into port with some number of M1A1s onboard. The ships are offloaded and proceed to another destination for their maintenance. The tanks from these ships may be transported to the active battalions for use or retained at the offload facility to be backloaded when the ship returns from maintenance. Because the tanks are not used during their time on the ship, and in light of the Marine Corps plan to balance usage among all the tanks of the fleet, rotating tanks between the MPS and active battalions is desired. As is the case with the operational units, however, tanks used in this manner must be replaced by the DMF before the ship redeploys. Figure 1 graphically illustrates the tank movements described

above. The letters above each arc denote the type of tank that may travel between the locations.

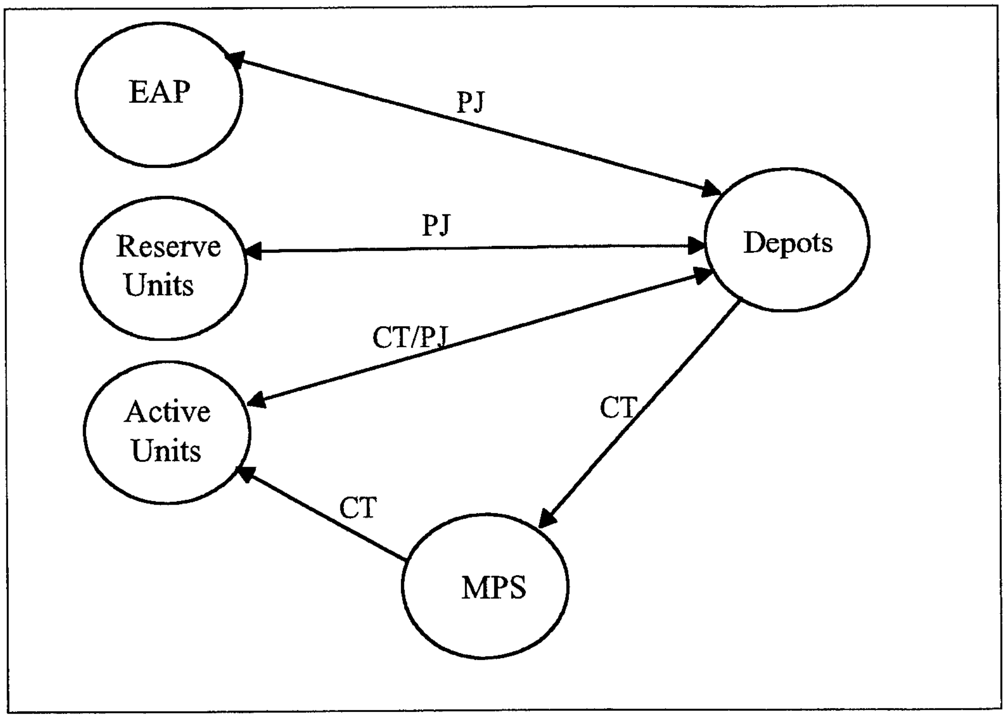

Figure 1. Possible Tank Rotation

C. OPERATIONAL CHARACTERISTICS

Tanks at different locations accumulate mileage at very different rates due to each location's unique operational tempo. For example, the open terrain and the CAX program at Twentynine Palms creates high usage of the tanks assigned to the 1st Tank Battalion and the Equipment Allowance Pool (EAP). Conversely, the close terrain and trafficability restrictions at Camp Lejuene, NC, result in lower usage of 2d Tank Battalion's tanks. Based on the mileage accumulated during fiscal year 1994, tanks at 1st Tank Battalion

accumulate an average of 309 operating miles per quarter while tanks at 2nd Tank Battalion average only 90 miles per quarter [Ref. 2].

The rate at which tanks accumulate mileage also determines the volume of tanks sent to depot by each battalion or operational unit. Like most complex equipment, every tank is not alike. Each has its own operating peculiarities that users can only discover and assimilate after a period of time. To avoid having to discover and assimilate operating peculiarities of unfamiliar tanks too often, there is a policy that each battalion will send at most 25% of its tanks for maintenance annually [Ref. 2] . This percentage is referred to as the turnover percentage, a parameter for controlling the influx of unfamiliar tanks to the battalions, hence maintaining unit stability in tank operations.

The main challenge in providing maintenance support is to ensure a maximum level of *readiness* at each unit. This thesis views the number of miles accumulated by a tank since its last depot maintenance as an indication of its *age* or degree of deterioration. So, more mileage means older, higher degree of deterioration, and less ready for training or combat. The next chapter discusses an optimal tank maintenance model that minimizes the average age of the Marine Corps' tank fleet.

III. MAINTENANCE PLANNING MODEL

The main objective in maintaining any equipment for military or industrial use is to increase the likelihood of the equipment functioning when needed. At the end of the last chapter, this likelihood is described as the degree of readiness which is measured as the mileage a tank accumulates between depot maintenance support. More miles means less ready and to be more ready is to have less mileage on tanks. This means that tanks should be sent to maintenance depots as often as possible. Of course, resources such as maintenance budgets, depot capacities and operational policies (e.g., immediate replacement and the annual turnover percentage) limit the number of tanks to receive depot level maintenance each year. So, the problem in maintaining the Marine Corps M1A1 tanks reduces to deciding when to send tanks to maintenance depots in order to achieve the minimum average mileage accumulation between depot maintenance without violating the operational restrictions and depot capacities.

The first section of this chapter lists the assumptions involved in modeling the optimal tank maintenance problem as a linear integer program. Section B describes the underlying network structure, and Section C states the corresponding mathematical formulation. Finally, the last section reviews previous research in equipment maintenance.

A. MODEL ASSUMPTIONS

The following assumptions are necessary to formulate the tank maintenance problem as an integer program.

1. Time is partitioned into quarters and maintenance related decisions are made at the beginning of each one. Since the lifecycle of the M1A1 is taken to be 20 years, the problem will consist of 80 quarters.

2. The mileage accumulated by tanks since the last depot maintenance is measured at the beginning of each quarter. Moreover, the mileage accumulated by a tank in a quarter is a constant. Under these assumptions, it is possible to calculate the mileage a tank accumulates by simply knowing the number of quarters it has been at the unit since its last maintenance. In particular, it is convenient to refer to this number of quarters as the *age* of a tank. So, if a tank is of age five at the beginning of quarter t, it means that the tank has been at the unit for five quarters since returning from the maintenance depot. If a tank at this unit accumulates 100 miles per quarter, the mileage accumulated since depot maintenance by this tank, at the beginning of quarter t, is 500 operating miles.

A tank of age zero means that it arrives from a depot at the beginning of the quarter. Having just received maintenance, it is logical to disallow an age zero tank to be sent to depot for maintenance.

3. The total time required to transport a tank to a depot and perform the necessary maintenance is no more than one quarter. Moreover, the time required to transport a tank from a depot to a unit is much less than a quarter. For modeling purposes, assuming that the latter time is instantaneous sufficiently approximates reality.

4. The depots can perform maintenance on both types of tank, CT and PJ. Depot capacity is stated as the number of tanks, regardless of the type, that a depot can provide

maintenance to in a given time period, i.e., one quarter. This assumption applies to both Marine Corps and Army depots.

B. NETWORK STRUCTURE

This thesis uses a network to account for the number, location and age of each type of tank. Graphically, a network is a collection of nodes and arcs. For this maintenance problem, there are two types of nodes, battalion and depot nodes. Both types represent the decision point at the beginning of each quarter. Battalion nodes are labeled with a pair of letters and numbers, (*Bi, Ak*). The letter *B* denotes an operational unit, i.e., a battalion, and the associated *i* is the unit designator. Similarly, *A* indicates that the associated letter *k* is the age. For example, a node labeled (*B1, A5*) represents tanks of age five at battalion 1. On the other hand, depot nodes are labeled with only one set of letter and numbers, *Dj*, where *D* is to indicate the node type and *j* is the depot designator. In Figure 2, the two sets or layers of nodes indicate the decision points at the beginning of quarter *t* and (*t*+1) for battalion 1 and for 2 depots, *D1* and *D2*. For each layer, there are only five battalion nodes to indicate that tanks at battalion 1 can be of age 0 to 4. Implicit in this figure is the fact that tanks of age four must be sent to one of the depots for maintenance.

Arcs emanating from each node represent maintenance related decisions, and they can be classified as aging, movement, and depot inventory arcs. Aging arcs always connect battalion node (*Bi, Ak*) to (*Bi, Ak+1*) and represent the decision not to send tanks of age *k* at battalion *i* to depot. As a result, the tank's age is increased by one at the beginning of

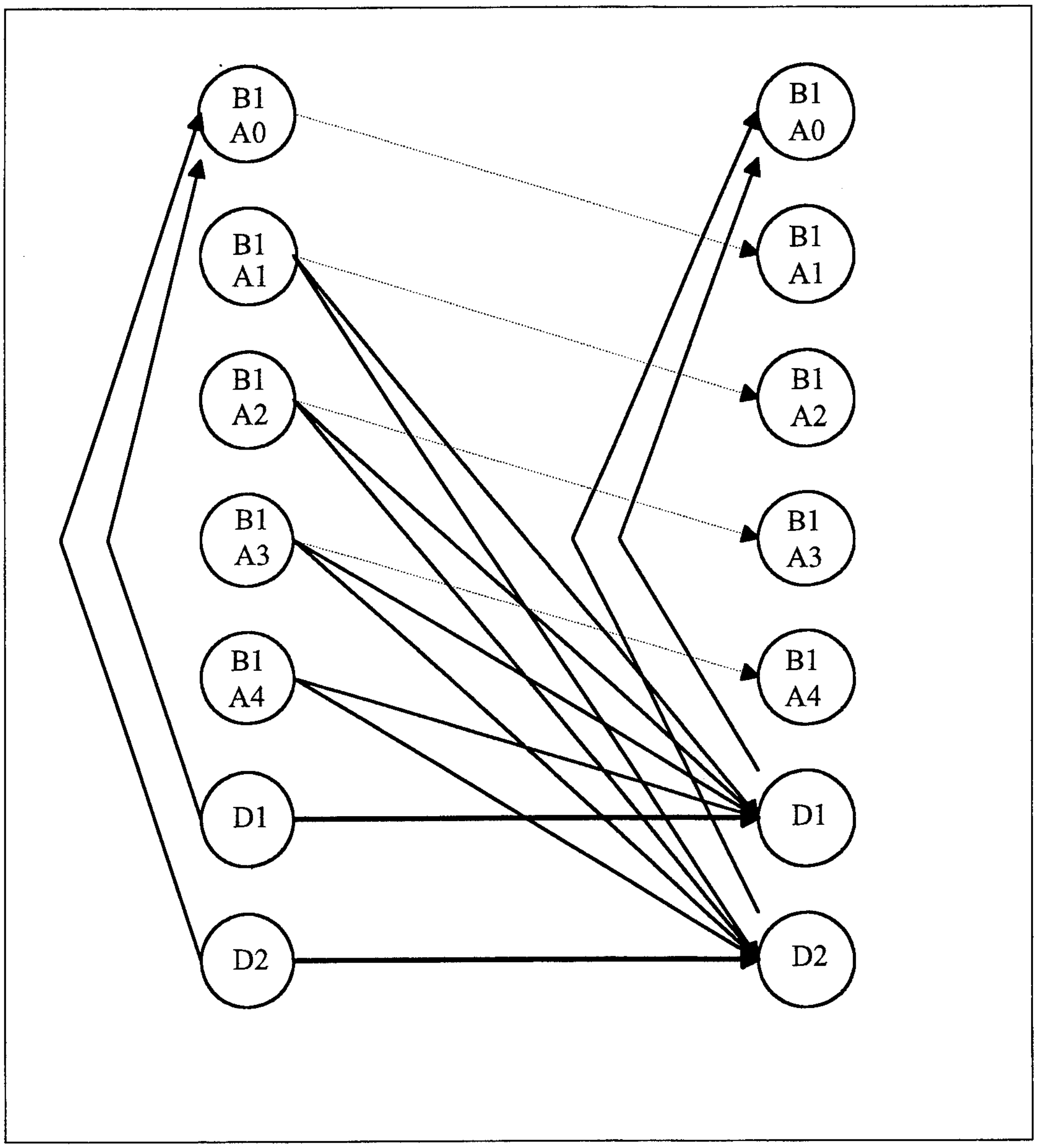

Figure 2. Network Structure

the next quarter. The aging arcs are drawn as dotted lines in Figure 2. Movement arcs connect a battalion node to a depot node and vice versa. Movement arcs from battalion node (*Bi, Ak*) to depot node *Dj* represents the decision to send tanks of age *k* at battalion *i* to depot *j* for maintenance, and they are referred to hence forth as *maintenance arcs.* By assumption 3 above, maintenance arcs indicate that the tanks are transported, receive maintenance and are ready to be sent back to perhaps different operational units at the beginning of the next quarter. In Figure 2, and with the exception of the age zero node, there are maintenance arcs connecting the battalion nodes at the beginning of quarter *t* to depot nodes *D1* and *D2*, at the beginning of quarter *t*+1. The other movement arcs, or *transportation arcs*, connect depot node *Dj* to battalion node (*Bi, A0*). These arcs represent replacement tanks being returned to battalions according to current policy. The nodes adjacent to each of these transportation arcs must be in the same quarter or layer to be consistent with assumption 4. Both movement arcs, i.e., maintenance and transportation, are displayed as thin solid lines in Figure 2. Finally, the depot inventory arcs connect a depot node in one quarter to another depot node with the same label in the next quarter. These arcs are the thick solid lines in Figure 2 and represent tanks with completed maintenance that are to remain at the depot until the next quarter.

In general, associated with each arc are a cost coefficient and a capacity. For the optimal tank maintenance problem, arcs are uncapacitated. To account for the mileage accumulated between depot maintenance, the cost associated with aging arcs emanating from battalion node (*Bi, Ak*) is *k* times the number of miles a tank accumulates in one

quarter at battalion or operational unit i. Otherwise, the arc cost is zero. To ensure that each depot capacity is not exceeded, the amount of flow on maintenance arcs terminating at each depot is restricted to be no larger than the quarterly depot capacity. Further, the combined yearly flow on maintenance arcs emanating from each unit is restricted to be no larger than the turnover percentage.

Given the initial number of tanks of various types and ages located at the operational units and depots, the integer programming problem is to find the amount of flow on each arc that yields the minimum average age between depot maintenance while satisfying the depot capacities as well as the operational restrictions. The problem is also multi-commodity in nature since the flow of M1A1 CTs must be distinguished from the flow of M1A1 PJs.

It is important to note that the problem as described above does not explicitly model tanks on the MPS ships. Including these MPS tanks does not embellish the model and preliminary experiments demonstrate that solutions from models with and without them are of the same quality. This is due to the fact that the availability of MPS tanks does not decrease the work load at the depots when time is divided into quarters. MPS tanks sent to battalions must be replaced by tanks from the depots before the ship redeploys in the same quarter. Instead of enlarging the already large model, the problem described above and the formulation below do not account for MPS tanks. If there is a requirement that tanks from each MPS ship be rotated with battalion tanks, then they are assumed to be

rotated with tanks in DMF instead. Since tanks in the DMF are eventually sent to battalions, the objective of balanced usage is implicitly maintained.

C. MATHEMATICAL FORMULATION

Mathematically, the optimal tank maintenance problem can be stated as follows:

Indices:

b, b'	battalions or operational unit, $b, b' = 1,\ldots,B$
d, d'	maintenance depots, $d, d' = 1,\ldots,D$
a, a'	tank age, $a, a' = 1,\ldots A_b$ where A_b denotes the maximum age for tanks in battalion b
t, t'	quarter, $t, t' = 1,\ldots,T$
y	year, $y = 1,\ldots,Y$
ty	tank type, ty = PJ, CT

Note that A_b must be predetermined. In theory, A_b can be any sufficiently large number. Setting A_b too large, however, produces an unnecessarily large number of decision variables.

Index Set:

Q_y	a set containing the index t (quarter) in year y, i.e., $Q_y = \{t : 4(y-1)+1 \le t \le 4y\}$

Data:

$IN_{b,a}^{ty}$	initial number of tanks of type ty at battalion b of age a
AM_b	average quarterly mileage for tanks at battalion b
RB_b^{ty}	number of tanks of type ty assigned to battalion b
TL_b	maximum number of tanks at battalion b to receive maintenance each year
DC_d	quarterly capacity of depot d
$DV1_d^{ty}$	number of tanks of type ty located at depot d at beginning of quarter one
$DV2_d^{ty}$	number of tanks of type ty located at depot d at beginning of quarter T

In the above definitions, $TL_b = \textit{turnover percentage} * (\sum_{ty} RB_b^{ty})$.

Variables:

$X^{ty}_{(b,a,t),(b,a+1,t+1)}$ number of tanks of type *ty* at battalion *b* of age *a* at the beginning of quarter *t* that become age *a+1* at the beginning of quarter *t+1*

$X^{ty}_{(b,a,t),(d,t+1)}$ number of tanks of type *ty* and of age *a* sent to depot *d* from battalion *b* at the beginning of quarter *t*

$X^{ty}_{(d,t),(b,0,t)}$ number of tanks of type *ty* sent to battalion *b* from depot *d* at the beginning of quarter *t*

$X^{ty}_{(d,t),(d,t+1)}$ number of tanks of type *ty* carried in maintenance float at depot *d* from quarter *t* to *t+1*

Formulation:

Optimal Tank Maintenance Problem

Minimize: $$\sum_{ty}\sum_{b}\sum_{a}\sum_{t}\left(aAM_b(X^{ty}_{(b,a-1,t-1),(b,a,t)}-\sum_{d}X^{ty}_{(b,a,t),(d,t+1)})\right)$$

Subject to:

$$X^{ty}_{(b,0,1),(b,1,2)}=IN^{ty}_{b,0}+\sum_{d}X^{ty}_{(d,1),(b,0,1)}\quad \forall ty,b \tag{1}$$

$$X^{ty}_{(b,0,t),(b,1,t+1)}=\sum_{d}X^{ty}_{(d,t),(b,0,t)}\quad \forall ty,b, and\ 2\le t\le T-1 \tag{2}$$

$$X^{ty}_{(b,a,1),(b,a+1,2)}+\sum_{d}X^{ty}_{(b,a,1),(d,2)}=IN^{ty}_{b,a}\quad \forall ty,b,a>0 \tag{3}$$

$$X^{ty}_{(b,a,t),(b,a+1,t+1)}+\sum_{d}X^{ty}_{(b,a,t),(d,t+1)}$$

$$=X^{ty}_{(b,a-1,t-1),(b,a,t)}\quad \forall ty,b,a>0, and\ 2\le t\le T-1 \tag{4}$$

$$X^{ty}_{(d,1),(d,2)}+\sum_{b}X^{ty}_{(d,1),(b,0,1)}=DV1^{ty}_{d}\quad \forall ty,d \tag{5}$$

$$X^{ty}_{(d,t),(d,t+1)}+\sum_{b}X^{ty}_{(d,t),(b,0,t)}=\sum_{a>0}\sum_{b}X^{ty}_{(b,a,t-1),(d,t)}\quad \forall ty,d, and\ 2\le t\le T-1 \tag{6}$$

$$DV2^{ty}_{d}+\sum_{b}X^{ty}_{(d,T),(b,0,T)}=\sum_{a>0}\sum_{b}X^{ty}_{(b,a,T-1),(d,T)}\quad \forall ty,d \tag{7}$$

$$\sum_{d}X^{ty}_{(d,1),(b,0,1)}-\sum_{d}\sum_{a}X^{ty}_{(b,a,1),(d,2)}=RB^{ty}_{b}-IN^{ty}_{b,a}\quad \forall ty,b \tag{8}$$

$$\sum_a X^{ty}_{(b,a,t-1),(b,a+1,t)} + \sum_d X^{ty}_{(d,t),(b,0,t)} - \sum_d \sum_a X^{ty}_{(b,a,t),(d,t+1)} = RB^{ty}_b$$

$$\forall ty, b, and\ 2 \le t \le T-1 \qquad (9)$$

$$\sum_a X^{ty}_{(b,a,T-1),(b,a+1,T)} + \sum_d X^{ty}_{(d,T),(b,0,T)} = RB^{ty}_b \quad \forall ty, b \qquad (10)$$

$$\sum_{ty} \sum_b X^{ty}_{(b,a,t-1),(d,t)} \le DC_d \quad \forall d, t \ge 2, a \ne 0 \qquad (11)$$

$$\sum_{ty} \sum_d \sum_{t \in Q_y} X^{ty}_{(b,a,t),(d,t+1)} \le TL_b \quad \forall b \qquad (12)$$

$$X^{ty}_{(l,a,t),(l',a',t')} \ge 0 \quad and\ integer \quad \forall ty, l, a, t \qquad (13)$$

The objective in the above formulation minimizes the total mileage accumulation between successive depot maintenance visits. The total mileage accumulation is determined for each unit by multiplying the number of tanks of a particular age a by the mileage accumulation per quarter at the unit, AM_b. The expression, $(X^{ty}_{(b,a-1,t-1),(b,a,t)} - \sum_d X^{ty}_{(b,a,t),(d,t+1)})$, describes the number of tanks of age a at the beginning of quarter t. The first term in the expression represents tanks remaining at the battalion from the previous quarter and the second term represents tanks sent to depot. The difference between these two terms gives the number of tanks of age a to remain at the battalion at the beginning of quarter t.

To simplify the presentation, the left and right sides of constraint sets (1) through (7) denote the flow out of and the flow into a node, respectively, in the network shown in Figure 2. Constraint sets (1) and (2) ensure the balance of flow at the battalion nodes for tanks of age zero. Constraint set (1) also allows for the initial distribution of tanks. Constraint sets (3) and (4) similarly provide for flow balance at battalion nodes for all ages

other than zero. Flow balance constraints for the depot nodes in quarter one, quarters two through *T-1*, and quarter *T* are given by (5) through (7) respectively. Constraint sets (5) and (7) additionally allow for the initial and final distribution of tanks at the depots. Constraint sets (8), (9), and (10) ensure the assigned number of tanks are kept at the battalions each quarter. For quarter one, the terms on the left side of (8) are the number of tanks received from depot minus the tanks sent to depot and the right side is the required number of tanks after allowing for the initial distribution. For the intermediate quarters, the first term on the left side of (9) represents tanks remaining at the battalion from the previous quarter, the second term states the number of tanks received from depot, and the third term represents tanks sent to depot. For the last quarter, the left side of (10) accounts for tanks remaining from the previous quarter and tanks received from depot. Note that tanks are not sent to maintenance in the last quarter. Constraint sets (11) and (12) observe the depot capacities and the annual turnover percentage, respectively. Lastly, constraint set (13) requires all decision variables to be nonnegative integers.

D. LITERATURE REVIEW

Many articles in the current literature deal with the modeling of maintenance systems. Pierskella and Voelker [Ref. 3] and Sherif and Smith [Ref. 4] provide overviews of the maintenance modeling literature. Luxhoj [Ref. 5] presents seven general categories of such literature emphasizing the modeling of durable equipment - equipment subject to normal wear and tear.

The approaches to modeling maintenance problems are extremely diverse. Klein and Rosenberg's [Ref. 6] linear programming models use Markovian deterioration to develop inspection, maintenance, and replacement policies. Schwartz et al. [Ref. 7] use dynamic programming to search for optimal maintenance policies for repair and replacement of naval aircraft. Bellman and Dreyfus [Ref. 8] first introduced the use of discrete dynamic programming to find optimal equipment service life. Finally, Taylor and Jackson [Ref. 9] apply queueing theory to determine appropriate levels for spare parts inventories.

Similar to the approach used by Frisch [Ref. 10] and Fabrycky [Ref. 11], the optimal tank maintenance problem in this thesis groups tanks at each operational unit into age groups in order to avoid tracking individual tanks. Frisch developed a model which places items with similar characteristics or operating environments into groups and used nested Markov chains to study spare parts requirements and repair and replacement alternatives. Fabrycky used the same methodology to model repairable equipment population systems (REPS). The REPS model employs finite queueing theory to evaluate the costs as well as the design of the service facility. The models used in Frisch and Fabrycky are stochastic in nature. As an alternative, the tank maintenance problem is an optimization problem in which all parameters are assumed to be known. This deterministic approach allows a variety of constraints to be included. Moreover, by varying the parameters between their extreme values, some issues dealing with uncertainty can be addressed indirectly.

This chapter outlined the assumptions, explained the structure, and gave a mathematical formulation of the optimal tank maintenance problem. In Chapter IV, the model is implemented using the General Algebraic Modeling System (GAMS) [Ref. 12], a sample problem is solved and several maintenance planning issues are addressed.

IV. IMPLEMENTATION AND APPLICATIONS

In the last chapter, the optimal tank maintenance problem is formulated as a linear integer program which maximizes the readiness of the tank fleet by minimizing the average mileage accumulation between depot maintenance. The first section of this chapter presents an example problem and the solution obtained from GAMS. In the last section, three maintenance related issues are analyzed to demonstrate the usefulness of the model as an aid in making policy decisions.

A. SAMPLE PROBLEM

The sample problem below models the five operational units and the two Marine depots for a period of 20 years. The example uses mileage data obtained from Marine Corps Systems Command (MARCORSYSCOM) and information on depot capacities from the Marine Corps Logistics Base, Albany, Georgia.

Table 2 below shows the average and standard deviation of the quarterly mileage accumulation at each operational unit. The data for 1st and 2nd Battalions are derived from mileage data reported to MARCORSYSCOM. The other units do not have data on the M1A1 tanks at the writing of this thesis. To complete Table 2, the average and standard deviation for the 8th Tank Battalion is assumed to be the same as the 2nd. Similarly, the 4th Tank Battalion and the EAP are assumed to have the same average and standard deviation as the 1st Tank Battalion. The last column represents the maximum age of a tank at each unit. This maximum age is simply the number of quarters that a tank

can operate at a unit before reaching the 5000 mile limit. Because of the low quarterly mileage accumulation for the 2nd and 8th Battalions, tanks can remain at these units for 13 years before reaching the 5000 mile limit and having to be sent for maintenance. Operationally, 13 years is too long for tanks to go without depot maintenance. For the example problem, the maximum age is simply set at five years or 20 quarters.

Unit	Average	Standard Deviation	Maximum Age
1st Battalion	309	71	16
2nd Battalion	90	26	20
4th Battalion	309	71	16
8th Batttalion	90	26	20
EAP	309	71	16

Table 2. Mileage Rates And Maximum Ages

To complete the specification of the sample problem, the initial ages of the tanks must be determined. As previously explained, the age of a tank represents the quarters of use since arriving at a unit from maintenance. Initial tank ages at each unit are assigned based on the number of quarters needed to accumulate the tank's present mileage as a function of the unit's quarterly mileage accumulation rate. Since the quarterly mileage accumulation rate at the 1st Battalion is 309 miles per quarter, an age of one is given to tanks with up to 309 miles, age 2 represents 310 to 618 miles, and similarly up to the maximum age of 16 for tanks with between 4692 and 5000 miles. The same methodology is used for 2nd Battalion with the corresponding mileage rate of 90 miles per quarter. Therefore, a tank

with an initial age of one has an initial mileage reading of less than 90, age two represents 91 to 180 miles, and the maximum age of 20 is given to tanks with between 1801 and 1890 miles. The maximum age of 20 at 2d Battalion is based on the assumption that depot maintenance is required at least once every five years regardless of the mileage. Table 3 displays the number of tanks at various ages for the five operational units. Lastly, the capacity at each depot is 12 tanks per quarter [Ref. 1].

Using the above data, the optimal tank maintenance problem implemented in GAMS generates 36,284 variables and 12,705 constraints. The OSL solver [Ref. 13] needed 674.29 CPU seconds to find an optimal solution on an IBM RS/6000 Model 590H computer. Since the output from GAMS for the problem is extensive, portions of the results are presented below.

Table 4 reports the status of the M1A1 CTs at 1st Battalion for the first five quarters under the 25% turnover percentage restriction. Each column displays the number of tanks in each age group at the beginning of the quarter. To verify the feasibility of the solution, the rows labeled *Total* and *Req Number* give the total and the required number of tanks stationed at the unit. Both numbers must be the same in every quarter to ensure that the solution is feasible. The row labeled *Average Age* gives the average mileage accumulated between depot maintenance by tanks at the unit. Table 4 shows that the common tanks at the 1st Battalion accumulate an average of 3213.6 miles between depot maintenance at the beginning of quarter one.

Age	1st Battalion	2nd Battalion	4th Battalion	8th Battalion	EAP
1		2			
2	2	2			
3	2	2			
4		2	2	2	
5	3		2	2	1
6			2	2	
7		4	3	3	
8	3	4	3	3	1
9	3		2		2
10	3	4	3	3	2
11	10	9	4	4	5
12	14	7	2	2	6
13	8	7	2	2	2
14	8	7	2	2	2
15	2	5	3	3	1
16					
17		1		1	
18					
19		1			
20		1		1	

Table 3. Tank Ages

Age	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 5
0	1	2	3		9
1		1	2	3	
2	1		1	2	3
3	1	1		1	2
4		1	1		1
5	2		1	1	
6		2		1	1
7			2		1
8	1			2	
9	1	1			2
10	1	1	1		
11	6	1	1	1	
12	8	6	1	1	1
13	4	8	6	1	1
14	4	4	8	6	1
15		2	3	8	6
16				3	2
Total	30	30	30	30	30
Req Number	30	30	30	30	30
Average Age	3,213.6	3,213.6	3,038.5	3,347.5	2,142.4
To Depot	1	2	3		9

Table 4. Summary Of M1A1 Common Tanks At 1st Battalion

As a summary, Table 5 gives the average mileage accumulated by tanks between depot maintenance at all five units on a quarterly basis.

Unit	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 5
1st Battalion	3,196.55	3,265.81	3,068.69	3,036.72	2,306.84
2nd Battalion	856.55	730.86	796.03	861.21	817.76
4th Battalion	3,061.91	2,963.59	3,061.91	3,160.23	2,345.59
8th Battalion	2,678	2,513.2	2,513.2	2,667.7	2,657.4
EAP	816	762	711	801	891

Table 5. Average Mileage Between Depot Maintenance

Table 6 shows that the number of tanks sent to the depots fluctuates quarterly. However, when summarized on a yearly basis as shown in Table 7, the number of tanks sent to depot is the same each year. This uniformity is due to the objective of minimizing

Depot	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 5
Albany	5	8	5	2	12
Barstow	7	12	8	5	12

Table 6. Depot Work Loads

the average mileage between depot maintenance. To reduce the average mileage between maintenance means to send more tanks to depots, but the number of tanks sent to depot is limited by either the depot capacity or the turnover percentage. In this example, the turnover percentage is more restrictive and allows only 52 tanks to be sent to depot yearly. On the other hand, based on a depot capacity of 12 per quarter, it is possible to

Unit	Year 1	Year 2	Year 3	Year 4	Year 5
1st Battalion	15	15	15	15	15
2nd Battalion	15	15	15	15	15
4th Battalion	8	8	8	8	8
8th Battalion	8	8	8	8	8
EAP	6	6	6	6	6
Total	52	52	52	52	52

Table 7. Yearly Totals Sent To Depot

maintain 96 tanks each year.

The totals shown in Table 7 are useful for preparing maintenance budgets. For example, multiplying the yearly total by the maintenance cost per tank; e.g., $200,000, gives the yearly budget for maintenance. For this example, the model recommends a $10.4 million budget to maintain the tanks. Moreover, the number of tanks sent to depot are a function of the turnover percentage and depot capacities. By varying these two parameters, users can increase or decrease the numbers in Table 7 as desired.

B. APPLICATIONS

The optimal tank maintenance problem as modeled in this thesis seeks to minimize the average mileage accumulation on tanks between depot maintenance. Through close scrutiny of the solution to this problem, valuable insight to policy planning and analysis is gained. Additionally, by resolving the problem with different data inputs and/or different constraints representing alternate maintenance policies, cost/benefit analyses of various

maintenance schemes can be performed. In the following sections, policy and planning issues are analyzed using the optimal tank maintenance model.

1. Number of Depots

Of concern to the Marine Corps is the use of the Army Depot at Anniston, Alabama. This depot provides maintenance at a higher cost than the other two Marine depots. To investigate the possibility of using only two Marine depots, the optimal tank maintenance problem is slightly modified.

When a tank does not receive maintenance after 5000 miles or five years of use, the tank is said to be in mileage violation. The tank incurs a violation for each quarter it does not receive maintenance as needed. To investigate the feasibility of using two or three depots, a new objective which is to minimize the number of violations during the 20 year horizon, i.e., minimize $\sum_{ty} \sum_{b} \sum_{a \geq A_b} \sum_{t} X^{ty}_{(b,a,t-1),(b,a+1,t)}$, replaces the one that minimizes average age. In addition, to enlarge the feasibility region, the turnover percentage is also relaxed. Solving this modified tank maintenance problem with two and three depots yields a large number of violations in both cases. However, when the utilization of depots are examined, much of the depot capacities is unused. So, depot capacities can not be a factor causing the violations. Examining the ratio of tanks at the units and tanks in the DMF demonstrates that there is one CJ tank in DMF for every four CJ tanks at the operational units. On the other hand, there is only one PJ tank in DMF for every 20 PJ tanks at the units. This indicates that the number of PJ tanks in DMF is insufficient. To reduce the number of violations, a number of PJ tanks must be transferred from the units to DMF. Figure 3 depicts the number of violations as a function of the number of PJs in DMF. The

results in Figure 3 assume only two Marine depots are used, each with a capacity of 12 tanks per quarter. From Figure 3, it is clear that it is possible to maintain tanks without any violations with two depots if there are 10 PJ tanks in DMF.

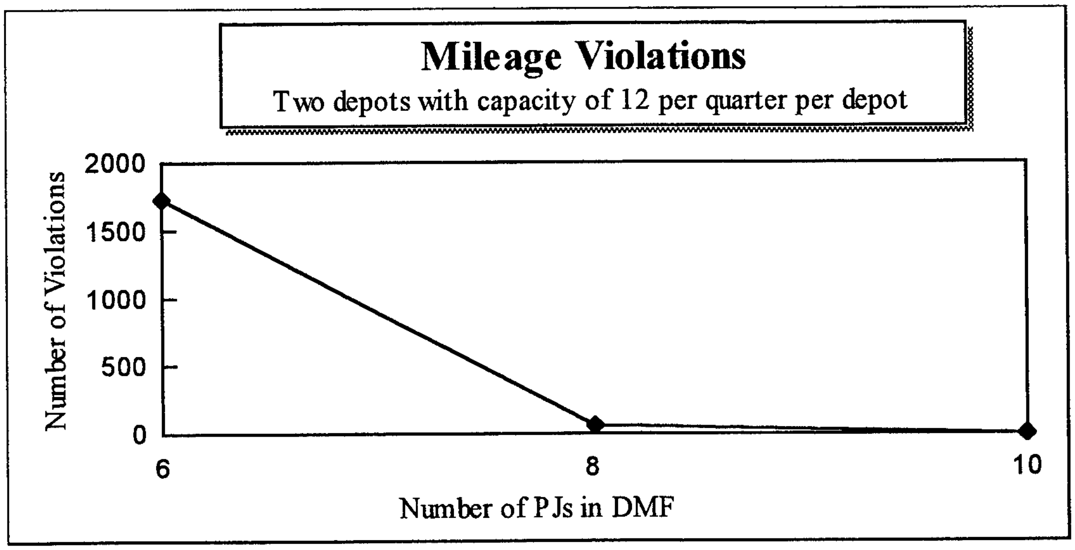

Figure 3. Mileage Violations vs. Number of PJs in DMF

2. Depot Capacity

The Marine depots are required by DoD to compete with all other depot maintenance activities and with private industry for maintenance contracts. Because of this, it is possible that the capacity available to support Marine tanks will fluctuate over time. Further, if the full capacity is available and the Marine Corps does not utilize it, the result is unused depot capacity that could otherwise be used more profitably. Obviously, knowing the capacity appropriate for the M1A1 fleet is beneficial to both the depot management and the Marine planners.

Figure 4 shows average mileage between depot maintenance over the 20 year horizon for two levels of usage, average and high. For average usage, the accumulated mileage is assumed to be the mean mileage in Table 2. For high usage, the accumulated

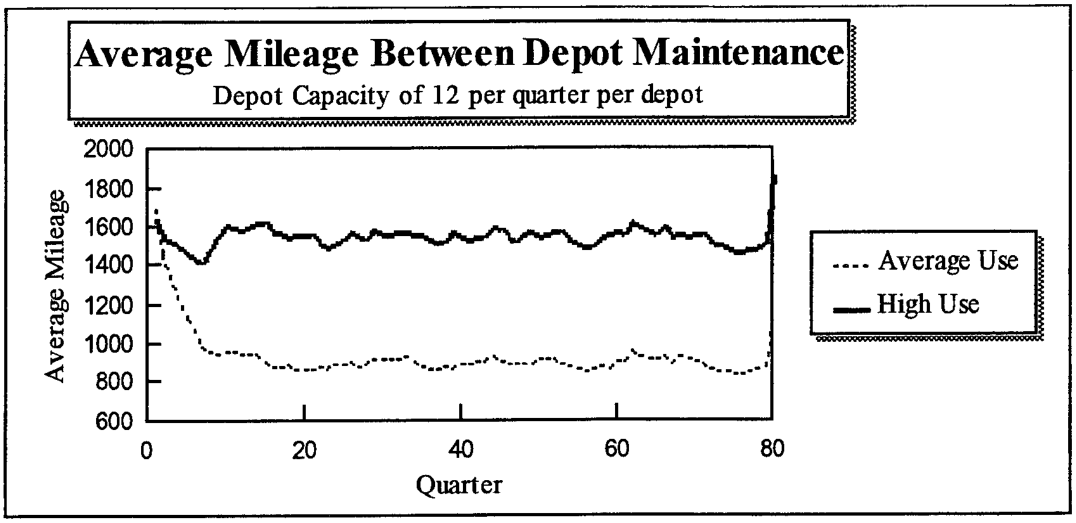

Figure 4. Average Mileage Between Depot Maintenance

mileage is the mean plus three times the standard deviation. The shape of the two curves is significant. During the early quarters, the model reduces the high mileage present on tanks at the beginning of quarter one. Similar high mileage occurs again at the last quarter in the planning horizon. This is due to the fact that tanks are not sent to depot at the beginning of quarter *T*. The relatively flat middle portion of both curves indicates a favorable steady state behavior when the depot capacities are set at 12 per quarter, in that average mileages are relatively low when compared to the 5000 mile limit. Overall, the steady state average mileage is approximately 20% and 30% of the 5000 mile limit for the average and high usage, respectively.

Figure 5 displays the average mileage over a 20 year period as a function of depot capacity. Recall that mileage between maintenance is a measure of readiness. Figure 5 shows how readiness varies with depot capacity. As average mileage decreases, readiness increases. Increasing depot capacity from six per quarter to eight decreases (increases) average mileage (readiness) by 26%. On the other hand, increasing from eight to 12

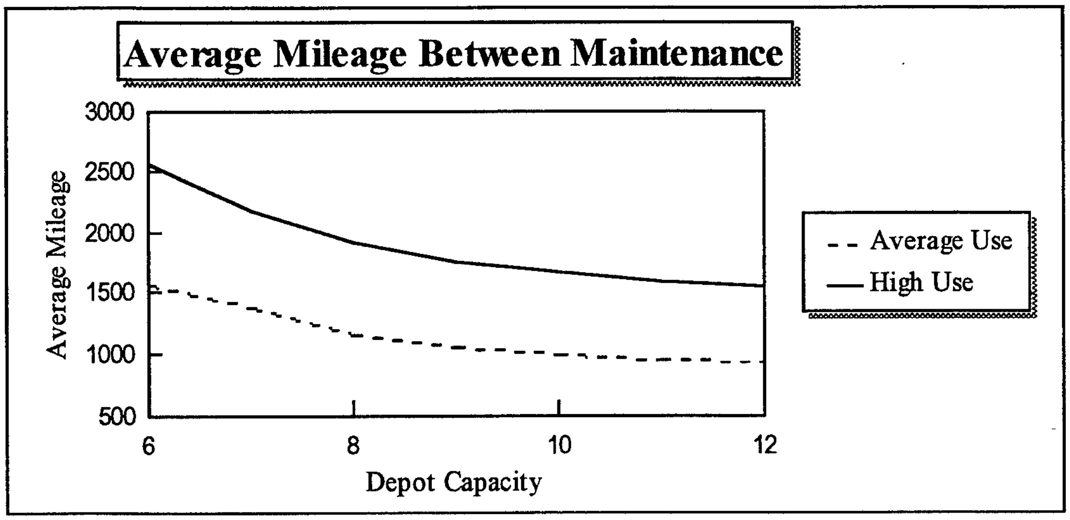

Figure 5. Average Mileage Between Maintenance (Readiness) vs. Depot Capacity

yields little change in average mileage and readiness. However, this observation is advantageous since it indicates that a variation in depot capacity between eight and 12 tanks per quarter has little effect on fleet readiness.

3. Turnover Percentage

As previously mentioned, the turnover percentage and depot capacity both limit the number of tanks to be sent for maintenance. In fact, these two problem parameters are related, in that one induces the other. In particular, the optimal tank maintenance model was solved without the turnover percentage constraint, but with varying depot capacities.

The results over a 10 year period and using an average usage rate are summarized in Figure 6. By limiting the depot capacity to six per quarter, no more than 26% of the tank fleet is sent to depot in a year. This 26% is called an *induced* turnover percentage. The term induced refers to the fact that the percentage is the result of sending tanks to depots in order to achieve the minimum average age. As the depot capacity increases, the

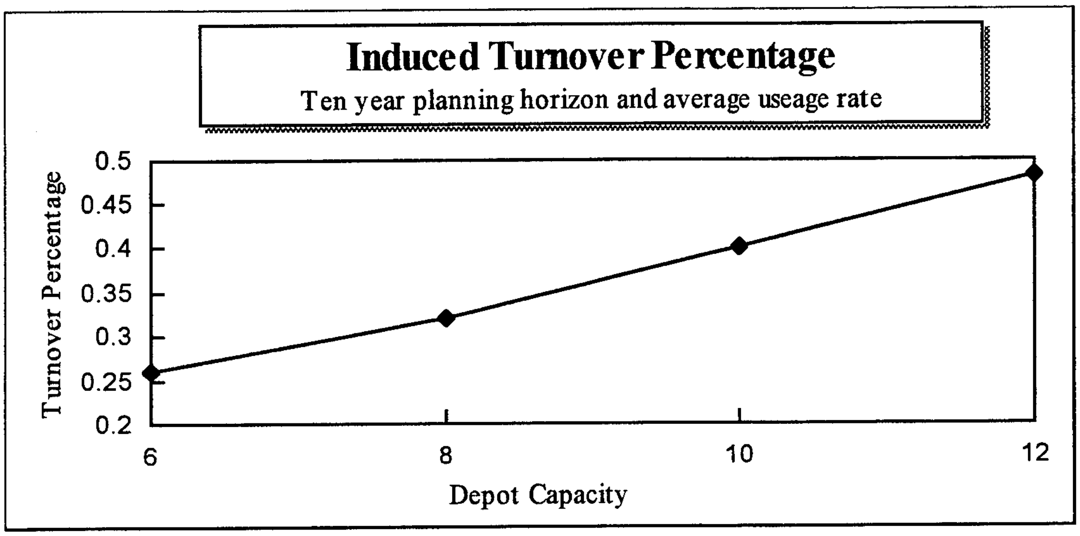

Figure 6. Induced Turnover Percentage

induced turnover percentage increases accordingly. At the capacity of 12 tanks per quarter at each depot, the induced turnover percentage is 48%. Since the desired turnover percentage is 25%, Figure 6 also suggests that the combination of 12 tanks per quarter capacity and 25% turnover percentage will yield higher average mileage than the same capacity with its induced turnover percentage. To illustrate the effect of having a turnover percentage smaller than the induced one, Figure 7 displays average mileages over 20 years for three turnover percentages, 25%, 35%, and 48%, the maximum rate with depot capacities of 12 tanks per quarter. The average mileage between depot maintenance

corresponding to the 48% turnover percentage represents the highest readiness possible with depot capacities of 12 per quarter. Figure 7 shows that average mileage (readiness) is increased (decreased) by an average of 19.8% and 38.67%, when the turnover percentage is reduced to 35% and 25% respectively. This demonstrates that there is a trade-off between readiness and unit stability as measured by the turnover percentage.

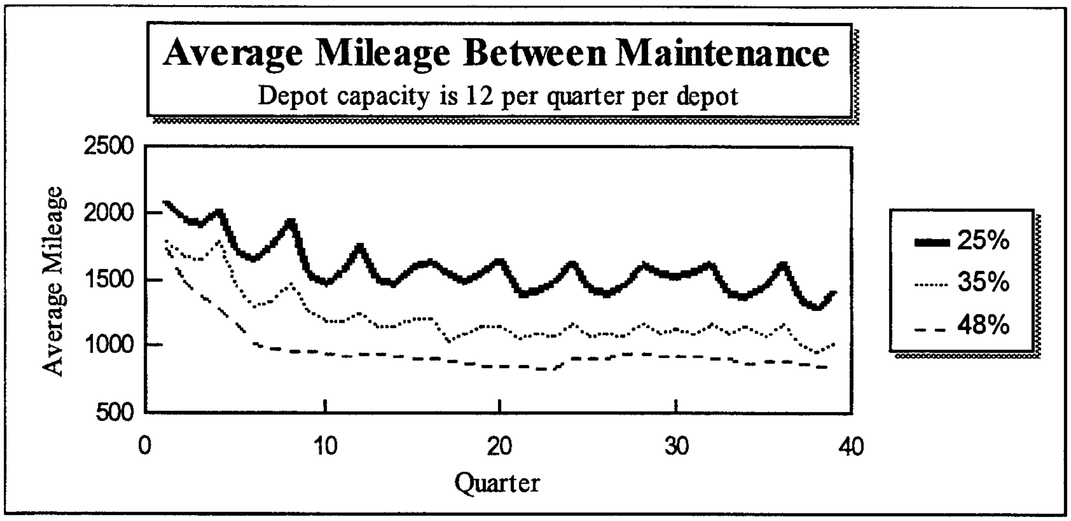

Figure 7. Average Mileage Between Maintenance vs. Turnover Percentage

In this chapter, the usefulness of the optimal tank maintenance model was demonstrated by investigating three maintenance related issues. These issues included the appropriate number and capacity of maintenance depots as well as the effect of the turnover percentage on fleet readiness. In the following chapter, the conclusions and recommendations of this thesis are given.

V. CONCLUSIONS AND RECOMMENDATIONS

> As our resource outlook declines in the future, it should be apparent to leaders at all echelons that the equipment we are driving, shooting, and communicating with today will be the equipment we must train and fight with for years to come. To maximize our readiness and combat capability, we must preserve our equipment through the prudent management of these scarce and expensive resources...[Ref. 14].

With this guidance in mind, maintenance planners are understandably concerned with ensuring that maintenance policies for all Marine Corps equipment contribute to combat readiness in a cost effective manner. Because of the cost of over 200,000 dollars per tank, there is significant interest in the planning and management of depot-level maintenance for the M1A1 tank fleet. The purpose of this thesis is to aid the Marine Corps in establishing an effective and efficient maintenance policy for the M1A1. Specifically, a linear integer program which maximizes fleet readiness while adhering to operational and policy constraints is formulated. The solution provides a tool for analyzing the effects of alternative maintenance proposals.

The optimal tank maintenance model is implemented in GAMS and is used to consider issues important to planning maintenance policies. The issues considered include the number of depots necessary to support the tank fleet and the planned distribution of the M1A1 PJs, the appropriate depot capacities, and the tradeoff between readiness and unit stability as measured by the unit turnover percentage. Based on a data set projected for 1996 and beyond, this research recommends that (i) only the two Marine depots are needed to support proposed maintenance policies and at least four additional M1A1 PJs should be reassigned to the DMF, (ii) a quarterly depot capacity of eight is sufficient since

increasing capacities from eight to 12 has little effect on readiness, and (iii) the tradeoff between readiness and unit stability warrants special attention in that increasing the turnover percentage from 25% to 35% and 48% improves readiness by 19.76% and 38.67%, respectively.

As a result of this thesis research, the following areas are submitted for future investigation.

1. Formulation of a minimum cost objective subject to a minimum level of readiness to provide explicit cost comparisons of maintenance policies. The possibility of using stochastic programming in the modeling of the transportation costs and other parameters should be explored.

2. A user friendly interface for the GAMS program is needed to allow planners to quickly analyze the effects of alternate maintenance proposals.

APPENDIX. GAMS PROGRAM CODE

The following text is a copy of the GAMS source code for solving the optimal tank maintenance problem.

```
$TITLE Depot Level Maintenance Planning System
$STITLE An optimization model written by Captain Jay Bargeron

*--------------GAMS AND DOLLAR CONTROL OPTIONS-------------------------------
$OFFUPPER OFFSYMLIST OFFSYMXREF
OPTIONS
        MIP = OSL, RMIP = OSL
        LIMCOL = 0 , LIMROW = 0, SOLPRINT = OFF , DECIMALS = 2
        RESLIM = 9999999, ITERLIM = 9999999, OPTCR = 0.03, SEED = 3141;

*----------------------------------------------------------------------------------------------
$ONTEXT
This model minimizes the mileage accumulated by tanks between successive depot-level
maintenance visits at each operational unit, subject to depot capacity and turnover
percentage constraints
$OFFTEXT

*-----------DEFINITIONS AND DATA---------------------------------------------------
SETS
L       tank locations /B1,B2,B3,B4,B5,D1,D2 /
B(L)    battalions or operational units /B1,B2,B3,B4,B5/
D(L)    maintenance depots /D1,D2/
A       age of tank /A0*A22/
T       number of quarters in planning horizon/T1*T80/
TY      tank type /C,P/
YR      year /Y1*Y20/;

ALIAS  (L, LP), (B, BP), (D, DP), (A, AP), (T, TP);

SCALAR

TOPERC    annual turnover percentage  /.25/

PARAMETERS
MA(B)          max age in quarters of tank before depot level maint reqd at battalion b
              /B1 14, B2 18, B3 14, B4 14, B5 18/
```

REQ(TY,B) number of tanks of type ty reqd at battalion b
/C.B1 30, C.B2 44, C.B3 0, C.B4 0, C.B5 0,
P.B1 28, P.B2 14, P.B3 22, P.B4 30, P.B5 30/

REQDMF(TY) number tanks to be maintained in depot maintenance float
/C 21, P 10/

DCAP(D) quarterly depot capacity
/D1 12, D2 12 /

COM(TY,L) 1 if type TY is located at location L and 0 otherwise
/C.B1 1, C.B2 1, C.B3 0, C.B4 0, C.B5 0, C.D1 1, C.D2 1,
P.B1 1, P.B2 1, P.B3 1, P.B4 1, P.B5 1, P.D1 1, P.D2 1/

AMIL(B) avg mileage accumulated per quarter at battalion b
/B1 309, B2 90, B3 309, B4 309, B5 90/

TOLIM(B) maximum yearly number of tanks to be sent to depot from battalion b;
TOLIM(B) = ROUND(SUM(TY, REQ(TY,B))*TOPERC);

TABLE INIT(TY,L,A) number of tanks of age a initially located at battalion b

	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19
C.B1			1	1		2			1	1	1	6	8	4	4	1				
P.B1			1	1		1			2	2	2	4	6	4	4	1				
C.B2		1	1	1	1			3	3		3	8	6	6	6	3		1		1
P.B2		1	1	1	1			1	1		1	1	1	1	1	2			1	
C.B3																				
P.B3						1			1	2	2	5	6	2	2	1				
C.B4																				
P.B4					2	2	2	3	3	2	3	4	2	2	2	3				
C.B5																				
P.B5					2	2	2	3	3		3	4	2	2	2	3		1		1

;

*------------------------------PROGRAM FORMULATION-----------------------------------

INTEGER VARIABLES

X(TY,L,A,T,LP,AP,TP) flow on arcs

DV1(TY,D) number tanks of type ty located at depot d in period 1

DV2(TY,D) number tanks of type ty located at depot d in last period

VARIABLES

TOTMILES	the total mileage accumulated on tanks between successive depot maintenance visits;

EQUATIONS

OBJ	obj function representing average miles accumulated between depot maintenance
B_A0(TY,B,T)	Flow balance constraints for battalion nodes, age zero
B_A1TOMAX(TY,B,A,T)	Flow balance constraints for battalion nodes, age > zero
D_T(TY,D,T)	Flow balance constraints for depot nodes
FIRSTPD(TY)	Ensures required number of tanks in DMF in first quarter
LASTPD(TY)	Ensures required number of tanks in DMF in final quarter
B_REQMNT(TY,B,T)	maintain reqd number of tanks at each battalion
D_CAP(D,T)	observe depot capacities each period
TOLIMYR(B,YR)	observe battalion turnover limit per year

```
OBJ..  TOTMILES =E= SUM((TY,B,A,T)$(ORD (A) GT 1 AND ORD(A) LE
                    MA(B)+3 AND COM(TY,B) EQ 1),
                    (AMIL(B)/100)*(ORD(A)-1)*INIT(TY,B,A)$(ORD(T)EQ 1)  +
                    (AMIL(B)/100)*(ORD(A)-1)*(X(TY,B,A-1,T-1,B,A,T) -
                                         SUM(D, X(TY,B,A,T,D,'A0',T+1))));

*Flow balance constraints for battalion nodes, age zero

B_A0(TY,B,T)$(ORD(T) LT CARD(T) AND COM(TY,B) EQ 1)..
        X(TY,B,'A0',T,B,'A1',T+1)
         =E=
        INIT(TY,B,'A0')$(ORD(T) EQ 1) + SUM(D, X(TY,D,'A0',T,B,'A0',T)) ;

*Flow balance constraints for battalion nodes, age > zero
B_A1TOMAX(TY,B,A,T)$(ORD(A) GT 1 AND ORD(A) LE MA(B)+3 AND
        COM(TY,B) EQ 1 AND ORD(T) LT CARD(T) )..
        SUM(D, X(TY,B,A,T,D,'A0',T+1)) +
        X(TY,B,A,T,B,A+1,T+1)$(ORD(A) LE MA(B) + 2)
         =E=
        INIT(TY,B,A)$(ORD(T) EQ 1) +
        X(TY,B,A-1,T-1,B,A,T)$(ORD(A) GT 1);
```

```
* Flow balance constraints for depot nodes
D_T(TY,D,T)..        X(TY,D,'A0',T,D,'A0',T+1)$(ORD(T) LT CARD(T)) +
                     SUM(B$(COM(TY,B) EQ 1), X(TY,D,'A0',T,B,'A0',T)) +
                     DV2(TY,D)$(ORD(T) EQ CARD(T))
                     =E=
                     X(TY,D,'A0',T-1,D,'A0',T)$(ORD(T) GE 2) +
                     DV1(TY,D)$(ORD(T) EQ 1) +
                     SUM((B,A)$(ORD(A) GT 1 AND ORD(A) LE (MA(B)+3)
                     AND COM(TY,B) EQ 1),
                     X(TY,B,A,T-1,D,'A0',T))$(ORD(T) GE 2);

FIRSTPD(TY).. SUM(D, DV1(TY,D)) =E= REQDMF(TY);
LASTPD(TY).. SUM(D, DV2(TY,D)) =E= REQDMF(TY);

B_REQMNT(TY,B,T)$(COM(TY,B) EQ 1)..
            SUM(A$(ORD(A) LE MA(B)+3), INIT(TY,B,A))$(ORD(T) EQ 1) +
            SUM(D,X(TY,D,'A0',T,B,'A0',T)) +
            SUM(A$(ORD(A) LE MA(B)+2), X(TY,B,A,T-1,B,A+1,T)) -
            SUM((D,A)$(ORD(A) GT 1 AND ORD(A) LE MA(B)+3),
            X(TY,B,A,T,D,'A0',T+1))$(ORD(T) LT CARD(T))
            =E=
            REQ(TY,B);

D_CAP(D,T)$(ORD(T) GE 2)..
            SUM((TY,B,A)$(ORD(A) GT 1 AND ORD(A) LE MA(B)+3 AND
            COM(TY,B) EQ 1), X(TY,B,A,T-1,D,'A0',T))
             =L=
            DCAP(D);

TOLIMYR(B,YR)..
            SUM((TY,D,T,A)$((4*(ORD(YR)-1)+1 LE ORD(T) AND ORD(T) LE
            4*ORD(YR)) AND (ORD(A) GE 2 AND ORD(A) LE MA(B)+3) AND
            COM(TY,B) EQ 1), X(TY,B,A,T,D,'A0',T+1))
            =L=
            TOLIM(B);

MODEL TANKS /ALL/;
SOLVE TANKS USING MIP MINIMIZING TOTMILES;
```

```
*-----------------------REPORT--------------------------------------------------------------
PARAMETER BTSUM(TY,L,*,T); OPTION BTSUM:2:1:1;
BTSUM(TY,B,A,T)$(ORD(A) LE MA(B)+3)  =  INIT(TY,B,A)$(ORD(T) EQ 1) +
        SUM(D,X.L(TY,D,'A0',T,B,'A0',T))$(ORD(A) EQ 1) +
        X.L(TY,B,A-1,T-1,B,A,T) - SUM(D,X.L(TY,B,A,T,D,'A0',T+1));
BTSUM(TY,D,'FR (T-1)',T) = DV1.L(TY,D)$(ORD(T) EQ 1) +
        X.L(TY,D,'A0',T-1,D,'A0',T)$(ORD(T) GT 1);
BTSUM(TY,D,'FIXED',T) = SUM((B,A)$(ORD(A) GT 1),X.L(TY,B,A,T-1,D,'A0',T));
BTSUM(TY,D,'TO BTN',T) = -SUM(B,X.L(TY,D,'A0',T,B,'A0',T));
BTSUM(TY,L,'TOTAL',T) = SUM(A, BTSUM(TY,L,A,T));
BTSUM(TY,B,'REQ NUM',T) =  REQ(TY,B);
BTSUM(TY,B,'OVER1',T) = SUM(A$(ORD(A) EQ MA(B)+1),
        X.L(TY,B,A,T-1,B,A+1,T));
BTSUM(TY,B,'OVER2',T)=
        SUM(A$(ORD(A) EQ MA(B)+2),X.L(TY,B,A,T-1,B,A+1,T));
BTSUM(TY,B,'OVER>2',T)=
        SUM(A$(ORD(A) EQ MA(B)+3), X.L(TY,B,A,T-1,B,A,T));
BTSUM(TY,B,'AVE AGE',T)$SUM(A, BTSUM(TY,B,A,T))=
SUM(A,AMIL(B)*(ORD(A)-1)*BTSUM(TY,B,A,T))/SUM(A,BTSUM(TY,B,A,T));
BTSUM(TY,B,'TO DEPOT',T)$(ORD(T) LT CARD(T))=
        SUM((D,A)$(ORD(A) GE 2 AND ORD(A) LE MA(B) +3),
        X.L(TY,B,A,T,D,'A0',T+1));

PARAMETER TRAF(TY,T,*,*); OPTION TRAF:2:1:1;
TRAF(TY,T,L,LP)$(ORD(L) NE ORD(LP)) =
        SUM((A,AP),X.L(TY,L,A,T,LP,AP,T+1));
TRAF(TY,T,L,'OUT') =        SUM(LP, TRAF(TY,T,L,LP));
TRAF(TY,T,'IN',LP) =        SUM(L,  TRAF(TY,T,L,LP));

PARAMETER AGE(*,T);
AGE(B,T)=
SUM((TY,A),AMIL(B)*(ORD(A)-1)*BTSUM(TY,B,A,T))/SUM((TY,A),
        BTSUM(TY,B,A,T));

PARAMETER WORK(*,*);
WORK(D,'CAP') = DCAP(D);
WORK(D,T)$(ORD(T) GT 1) = SUM(TY,BTSUM(TY,D,'FIXED',T));
PARAMETER TURNOV(*,*);
TURNOV(B,'LIMIT') = TOLIM(B);
TURNOV(B,YR) =
        SUM((TY,T)$(4*(ORD(YR)-1)+1 LE ORD(T) AND ORD(T) LE 4*ORD(YR)),
        BTSUM(TY,B,'TO DEPOT',T));
TURNOV('TOTAL',YR) = SUM(B,TURNOV(B,YR));
```

```
PARAMETER OVER5K(*,*); OPTION OVER5K:2:1:1;
OVER5K('OVER 1',T) = SUM((TY,B), BTSUM(TY,B,'OVER 1',T));
OVER5K('OVER 2',T) = SUM((TY,B), BTSUM(TY,B,'OVER 2',T));
OVER5K('OVER>2',T) = SUM((TY,B), BTSUM(TY,B,'OVER>2',T));
OVER5K('TOTAL',T) =
        SUM((TY,B), BTSUM(TY,B,'OVER 1',T)) + SUM((TY,B),
        BTSUM(TY,B,'OVER 2',T)) +SUM((TY,B), BTSUM(TY,B,'OVER>2',T));

*The following settings allow the text file to be imported into a spreadsheet for analysis

FILE RES /'tanks.txt'/;
PUT RES;
RES.PC = 5;

*--------------------------------TEXT FILE OUTPUT--------------------------------------------
PUT ' ';
PUT 'AVG AGE';
PUT /;
PUT ' ';
LOOP(B,PUT B.TL);
PUT /;
LOOP(T,PUT T.TL;
        LOOP (B, PUT AGE(B,T);
    .   );
        PUT /;
 );

PUT ' ';
PUT 'WORK';
PUT /;
PUT ' ';
LOOP (D, PUT D.TL);
PUT /;
LOOP (T, PUT T.TL;
        LOOP(D,  PUT WORK(D,T);
        );
       PUT/;
 );

PUT ' ';
PUT 'OVERALL TURNOV';
PUT /;
```

```
PUT ' ';
LOOP(YR, PUT YR.TL;

PUT (TURNOV('TOTAL',YR)/(SUM((TY,B), REQ(TY,B))));
PUT /;
);

PUT ' ';
PUT 'UNIT TURNOV';
PUT /;
PUT ' ';
LOOP (B, PUT B.TL);
PUT /;
LOOP (YR, PUT YR.TL;
        LOOP(B,  PUT (TURNOV(B,YR)/(SUM(TY, REQ(TY,B))));
        );
       PUT/;
 );

PUT ' ';
PUT 'MILEAGE VIOL';
PUT /;
LOOP (B, PUT B.TL);
PUT /;
LOOP (T, PUT T.TL;
        LOOP (B, PUT OVER5K(B,T);
         );
        PUT /;
);

DISPLAY  DV1.L, DV2.L, BTSUM, TRAF,  AGE, WORK, TURNOV, OVER5K;
```

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